

ELEVATED TEMPERATURE CRACK GROWTH

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The propagation of a crack in hot path components such as combustor liners can occur under complicated thermo-mechanical loading histories which may include substantial inelastic deformation. Current methods of predicting crack growth behavior utilizes linear elastic fracture mechanics (LEFM) which is not accurate for these circumstances. Therefore, it is desirable to determine suitable non-linear fracture mechanics parameters. The most likely parameters appear to be path-independent (P-I) integrals, several of which can be applied to high temperature inelastic crack growth problems. A combined analytical and experimental evaluation of these parameters is being performed at elevated temperatures under isothermal and thermo-mechanical loading, both with and without thermal gradients and hold times.

Several path-independent (P-I) integrals have been reviewed to determine their limitations under thermo-mechanical loadings. The basis for selecting candidate P-I integrals was that they were path-independent for these complex loading conditions. Based on these results, the following integrals were selected for more extensive evaluations

1. Blackburn's J^* -Integral and its rate form \dot{J}^*
2. Kishimoto's \hat{J} -Integral and its rate form $\dot{\hat{J}}$
3. Atluri's ΔT^* - and \dot{T}^* -Integral

Alloy 718 crack growth experiments were conducted to assess the ability of the selected P-I integrals to describe the elevated temperature crack growth behavior. These tests were performed on single edge notch (SEN) specimens under displacement control with multiple extensometers to monitor the specimen and crack mouth opening displacement (CMOD). The displacements in these tests were sufficiently high to

induce bulk cyclic inelastic deformation of the specimen. Under these conditions, the LEFM parameter K does not correlate the crack growth data. The experimentally measured displacements gradient at the end of specimen gage length were used as the boundary conditions in elastic-plastic finite element method (FEM) analyses. These analyses were performed with a node release approach using CYANIDE, a GEAE FEM code, which included a gap element which is capable of efficiently simulating crack closure. Excellent correlation was obtained between the experimentally measured and predicted variation of stress and CMOD with crack length and the stress-CMOD loops for Alloy 718 tests conducted at 538°C. This confirmed the accuracy of the FEM crack growth simulation approach. The experimentally measured crack growth rate data correlated well the three selected P-I integrals. The selection of the most accurate parameter will be based on analysis of temperature gradient and thermal mechanical fatigue crack growth experiments performed using Alloy 718.

It is currently planned to model crack growth under time dependent deformation using the superposition of the crack growth from cyclic or time-independent deformation and that from static or time-dependent deformation. The latter crack growth may be described using rate integrals (\dot{J}^* , $\dot{\hat{J}}$, and \dot{T}^*). The software for computation of these P-I integrals from FEM analyses has been developed. The P-I integrals in an SEN specimen have been calculated for both uniform load and uniform strain under isothermal conditions and for uniform load with a linear temperature gradient. The FEM analyses showed the relaxation and redistribution of the normal stress which occurs as a result of the time-dependent deformation. The three rate P-I integrals (\dot{J}^* , $\dot{\hat{J}}$, and $\dot{\Delta T}^*$) and their rate integrals (\dot{J}^* , $\dot{\hat{J}}$, and \dot{T}^*) were obtained with reasonable accuracy and showed path-independence for the conditions evaluated.

These investigations have produced significant progress in developing P-I integrals as non-linear fracture mechanics parameters. The analytical and experimental results to date suggests that this methodology has the potential of accurately describing elevated temperature crack growth behavior under the combined influence of thermal cycling and bulk elastic-inelastic deformation states.

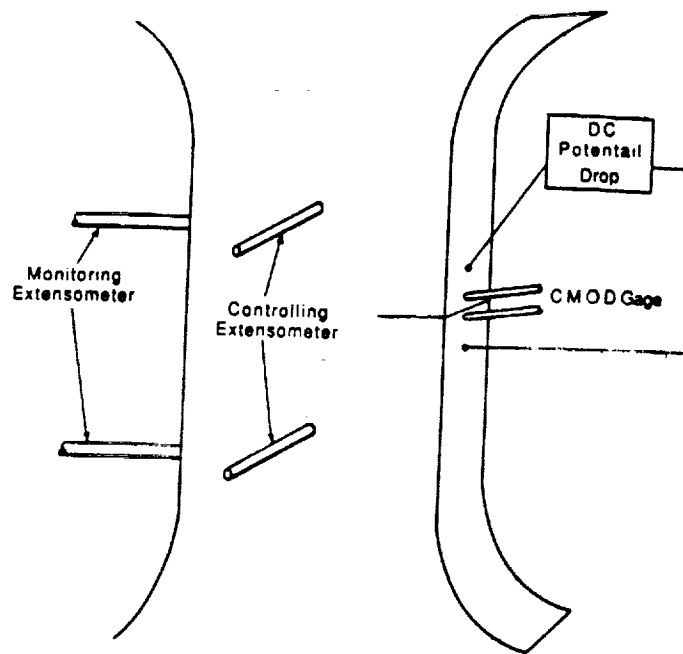
This work was performed under contract NAS3-23940 with the NASA-Lewis Research Center. T.W. Orange is the Program Manager.

TIME INDEPENDENT P-I INTEGRALS

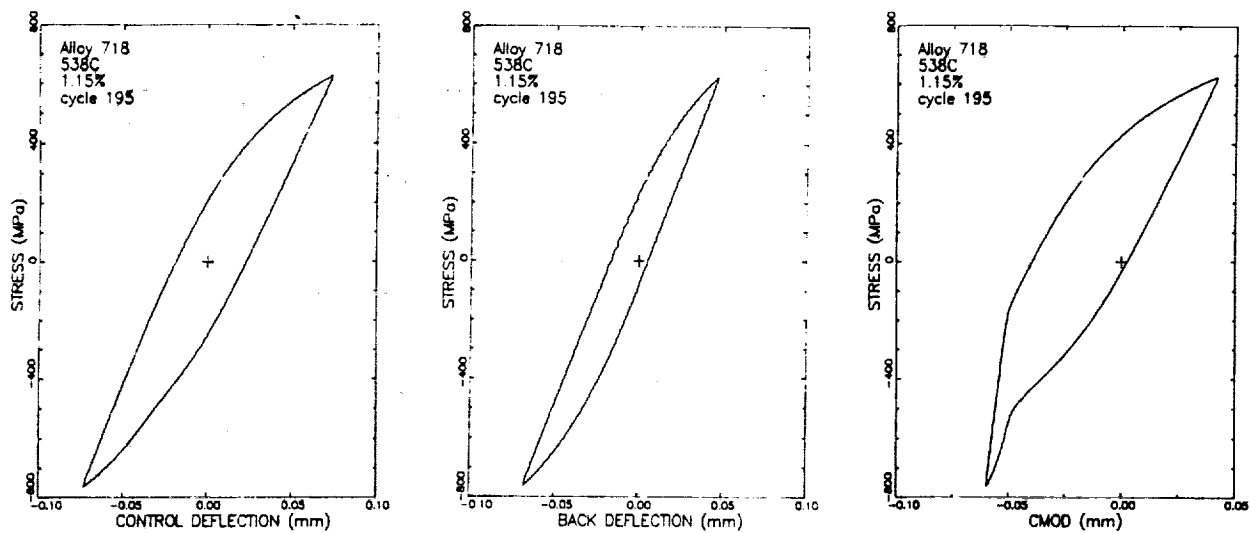
<u>P-I INTEGRAL</u>	<u>NON-PROPORTIONAL CYCLIC LOADING</u>	<u>TEMPERATURE GRADIENT</u>	<u>MATERIAL INHOMOGENEITY</u>	<u>ELASTIC-PLASTIC STRAINS</u>
RICE	NO	NO	NO	YES
AINSWORTH	NO	YES	NO	YES
WILSON & YU	NO	YES	NO	NO
GURTIN	NO	YES	NO	NO
BLACKBURN	YES	YES	YES	YES
KISHIMOTO	YES	YES	YES	YES
ATLURI	YES	YES	YES	YES

TIME DEPENDENT P-I INTEGRALS

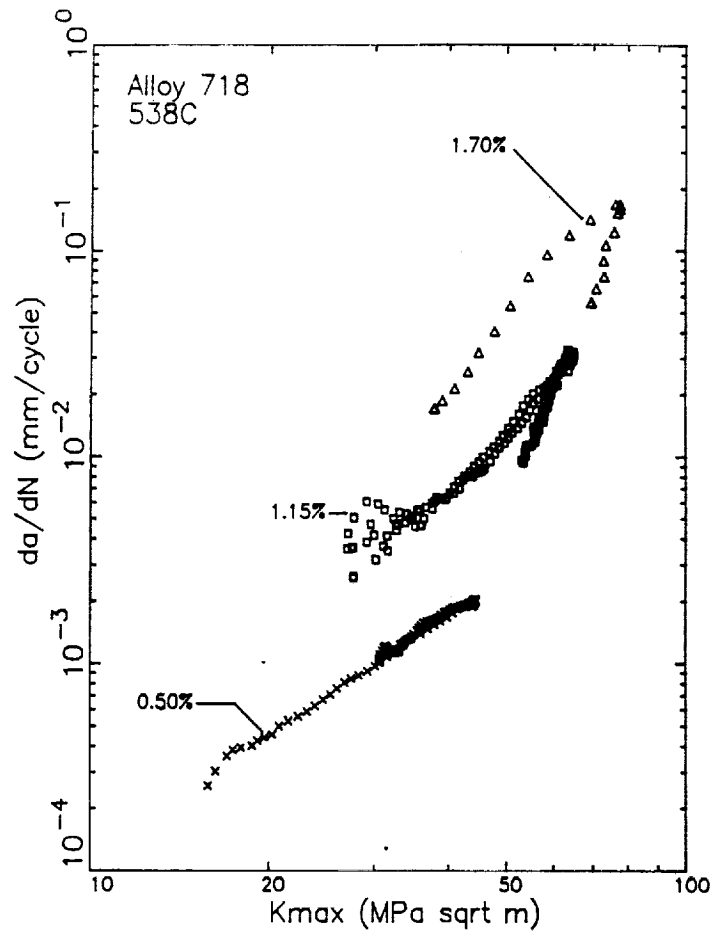
<u>P-I INTEGRAL</u>	<u>NON-PROPORTIONAL CYCLIC LOADING</u>	<u>CREEP DEFORMATION</u>	<u>TEMPERATURE GRADIENT</u>	<u>MATERIAL INHOMOGENEITY</u>
BLACKBURN	YES	YES	YES	YES
KISHIMOTO	YES	YES	YES	YES
ATLURI	YES	YES	YES	YES
HUTCHINSON GOLDBERG LANDES & BEGLEY	NO	STEADY STATE ONLY	NO	NO



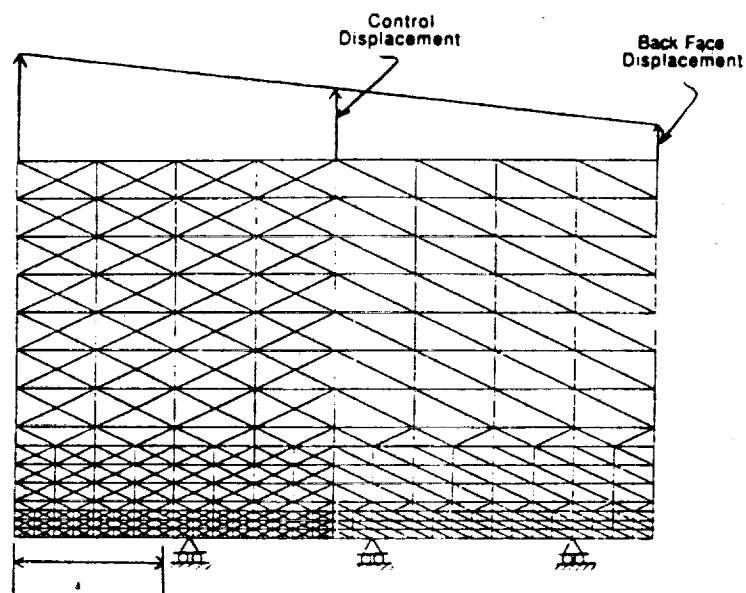
SCHEMATIC DIAGRAM OF TESTING METHOD



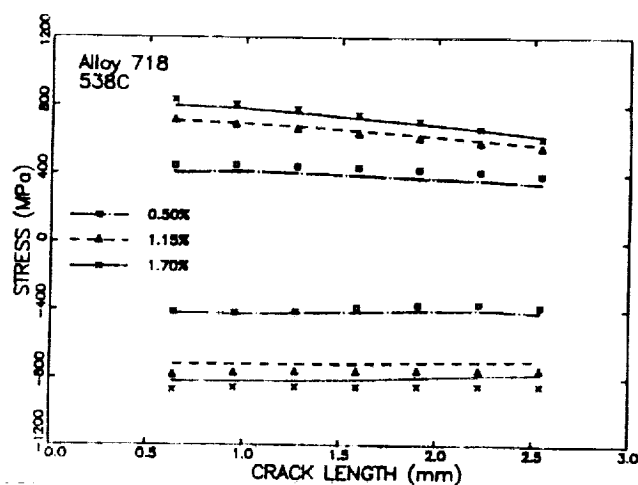
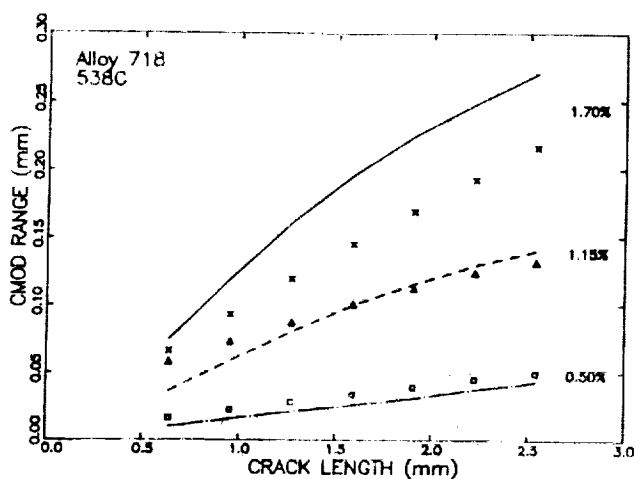
HYSTERESIS LOOPS FROM
538C ALLOY 718 TEST WITH
A STRAIN RANGE OF 1.15%
AND A MEAN STRESS OF ZERO



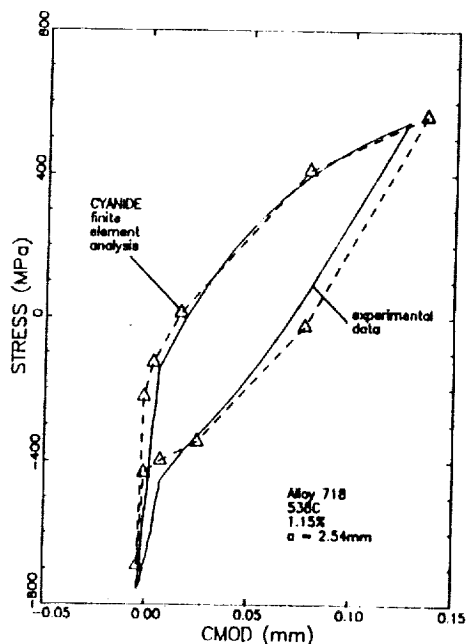
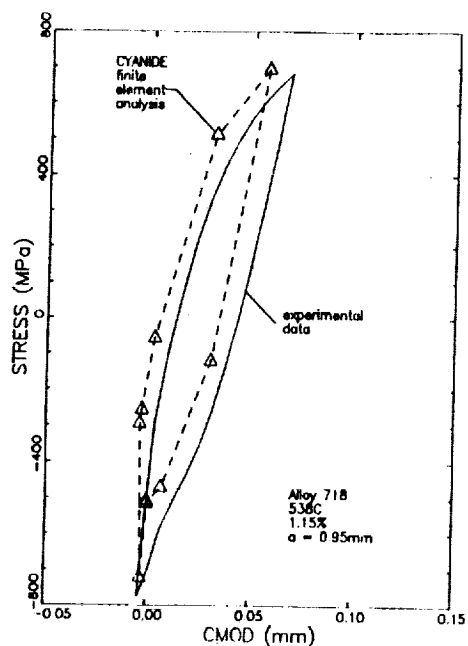
VARIATION OF CRACK GROWTH RATE WITH K_{MAX} IN 538C ALLOY 718 TESTS



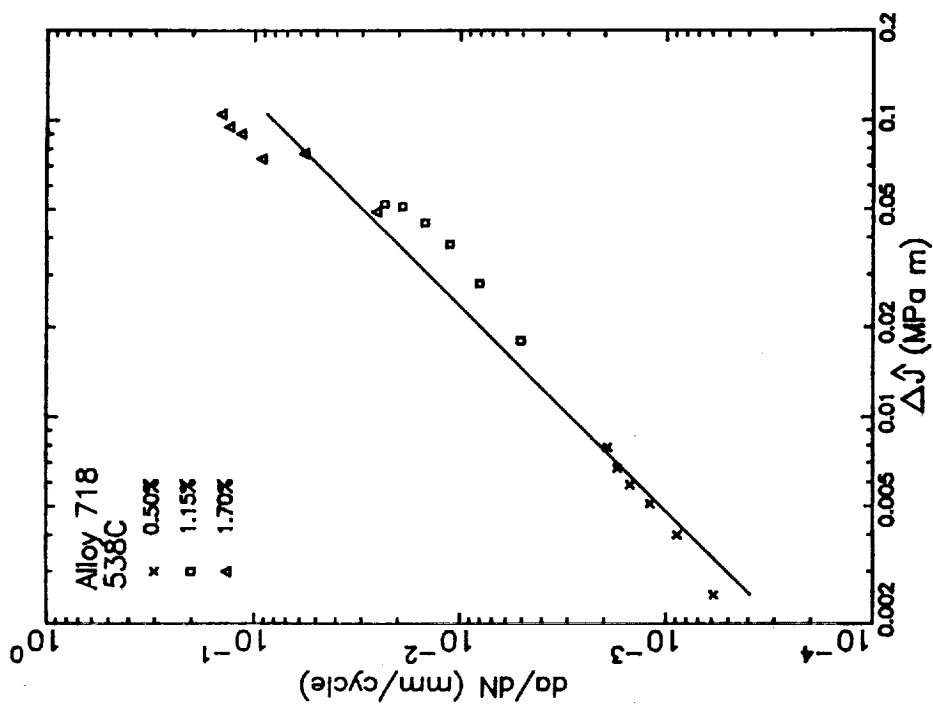
FINITE ELEMENT MESH
AND LINEAR DISPLACEMENT BOUNDARY CONDITIONS



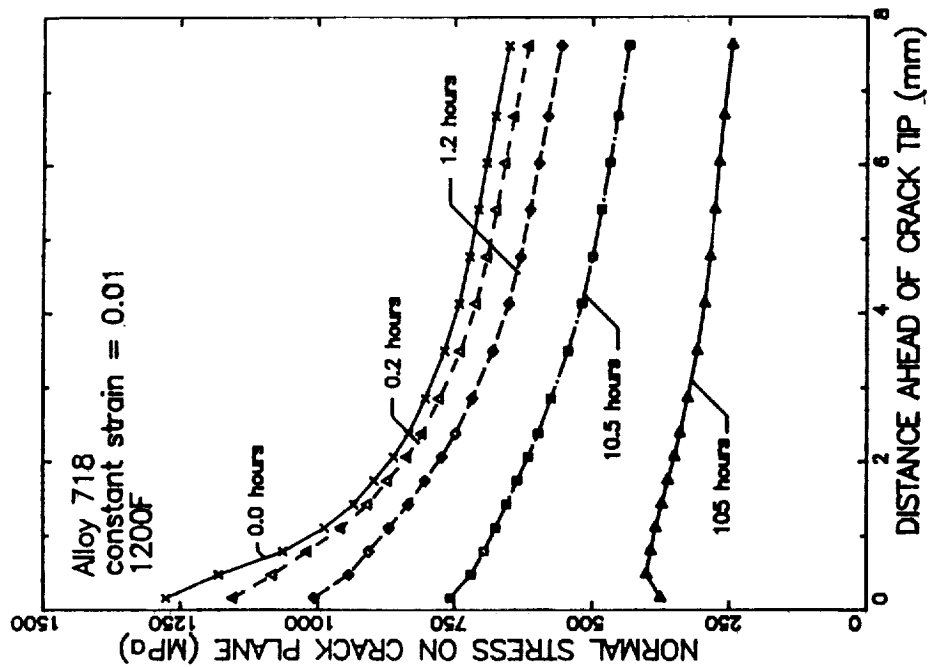
COMPARISON OF EXPERIMENTALLY MEASURED
AND PREDICTED VARIATION OF STRESS AND CMOD
WITH CRACK LENGTH IN 538C ALLOY 718 CRACK GROWTH TESTS



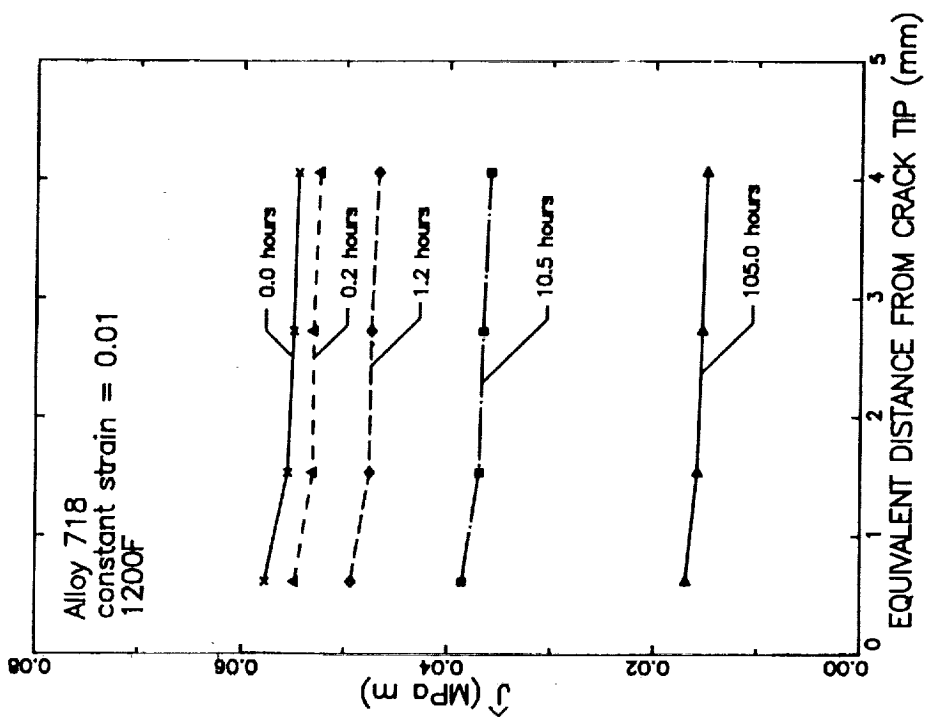
COMPARISON OF EXPERIMENTALLY MEASURED AND PREDICTED
STRESS - CMOD HYSTERESIS LOOPS FOR TWO CRACK LENGTHS
IN 538C ALLOY 718 CRACK GROWTH TESTS



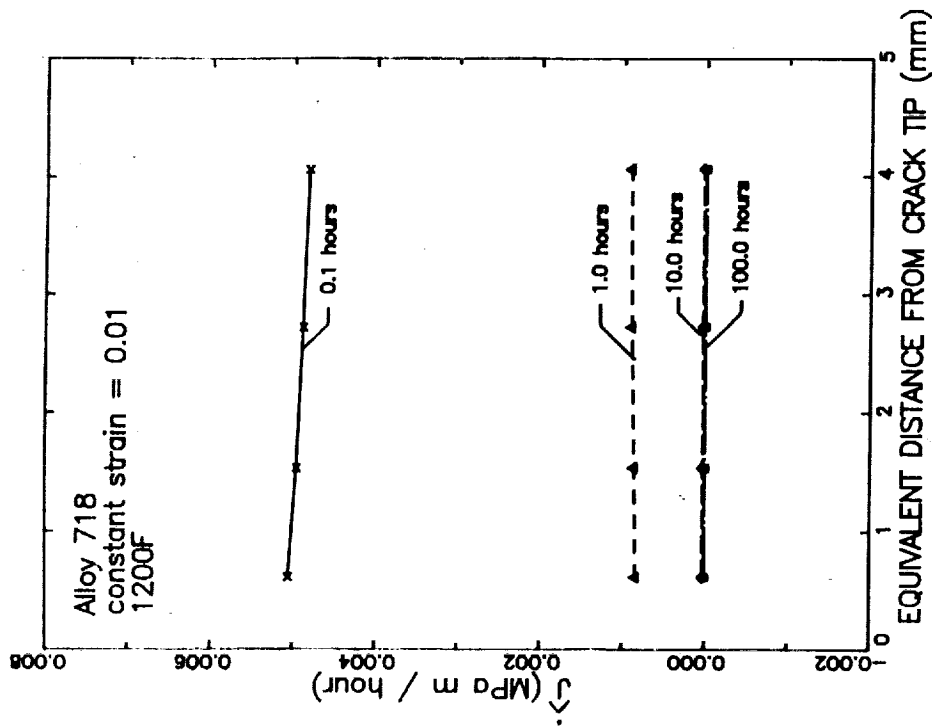
VARIATION OF CRACK GROWTH RATE WITH \hat{J}
IN 538C ALLOY 718 TESTS



NORMAL STRESS REDISTRIBUTION AHEAD OF CRACK TIP
IN A SEN SPECIMEN WITH A CRACK LENGTH OF 2.54 MM
AT DIFFERENT TIMES FOR A CONSTANT STRAIN OF 0.01



VARIATION OF \hat{J} WITH DISTANCE FROM CRACK TIP
IN A SEN SPECIMEN WITH A CRACK LENGTH OF 2.54 mm
AT DIFFERENT TIMES FOR A CONSTANT STRAIN OF 0.01



VARIATION OF \hat{J} WITH DISTANCE FROM CRACK TIP
IN A SEN SPECIMEN WITH A CRACK LENGTH OF 2.54 mm
AT DIFFERENT TIMES FOR A CONSTANT STRAIN OF 0.01